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# Functional evaluation of the knee following ACL reconstruction: A complex dynamical systems perspective

DANIELE ALBANO , BENEDETTA ROMANO, RODOLFO VASTOLA

*Department of Human, Philosophical and Educational Sciences, University of Salerno, Fisciano, Italy*

**ABSTRACT**

In sports, anterior cruciate ligament (ACL) injuries are very frequent and, in most cases, it is necessary to resort to surgical reconstruction to restore the functionality and stability of the knee joint. For the experts, the fundamental clinical result is represented by the return to sport at the pre-injury level. Return to the sport, however, is complex and multifactorial. A functional asymmetry present after the resumption of sports activity is, in fact, a sign of a reduced ability of the knee to absorb dynamic forces. The dynamical systems theory (DST) applied to biological systems has emphasized the importance of the variability present in human movement, as a basis for the processes of adaptation to the surrounding environment. The human body is a complex and nonlinear system (a small input can produce a big change), therefore nonlinear analysis tools have been proposed to analyse its behaviour. This brief review provides an overview of the nonlinear analysis tools used in the past twenty years in the functional evaluation of the knee following ACL reconstruction. The analysis of kinematic variability of the knee provides important information on the changes in neuromuscular function that occur after the rupture and reconstruction of the ACL. This kind of analysis can lead to an understanding of the joint's ability to provide proprioceptive information and how the whole system processes them. The functional evaluation of the knee using nonlinear analysis tools could represent a new and more suitable functional measurement of the joint for the return to sport.

**Keywords**: Anterior cruciate ligament; Complex dynamical systems theory; Kinematic variability; Motion analysis; Nonlinear analysis.

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**Corresponding author.** *Department of Human, Philosophical and Educational Sciences, University of Salerno, Fisciano, Italy.* https://orcid.org/0000-0002-4670-1115
E-mail: dalbano@unisa.it
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## INTRODUCTION

Complex dynamic systems are systems that evolve, with many interacting parts all able to influence the overall results of the system. Nonlinear complex dynamic systems are complex dynamic systems whose evolution over time is characterized by exchanges between the system and the surrounding environment and are non-proportional systems. The variables, dynamic or behavioural, of a complex dynamic system converge in a stable state in which, under certain sets of constraints, they can remain indefinitely, this state is called attractor as it attracts all the initial neighbouring states of the system. The antipode of the attractor is the repeller that pushes all the initial states away from it. Nonlinear complex dynamical systems are characterized by the presence of repellers and this allows them to enjoy more stable behavioural solutions for the same set of constraints (multi-stability). Complex systems have intrinsic noise, that is, random processes that do not allow the system to remain in an attractive state. For this reason, the system has fluctuations around the attractor, these cause the system to explore its own motion pattern production capabilities to find balance. In nonlinear systems there can be multiple attraction basins separated by barriers above which the repeller is located, the system, therefore, is equilibrated locally and not globally, since even if it is in one basin of attraction it can move to another (metastability). The global equilibrium depends on the height of the barriers and the strength of the fluctuations (Davids et al., 2014).

The theory of complex dynamic systems (DST) therefore describes the movement through two components, the attractors and repellers and offers a new perspective not only as regards the description of the movement but also for its control, in fact, the execution movement is affected by the environment in which it is performed. The distribution of attractors and repellers is self-organized and this allows nonlinear systems to be flexibles and to adapt to different circumstances. DST applied to biological systems has underlined the importance of the variability present in human movement as a basis for the processes of adaptation to the surrounding environment. The variability of human movement, in fact, can be defined as the variations in motor performance during practice and the repetitions of an action. From this point of view, human locomotion has a series of variations that in healthy and normal conditions fluctuate over time. The fluctuations between the steps seem to be noisy, that is, they seem to vary without any correlation between one step and another, but, the locomotor system has a motor memory, hence the fluctuations between one step and another are not random but contain a subtle and hidden temporal structure. Studying this time organization can provide information on how movements are controlled to maintain a stable and flexible pace. Complex path fluctuations are, therefore, responsible for flexible adaptations to stresses. Therefore, optimal variability could be described as a healthy state characterized by the greatest possible effective complexity. This variability has a deterministic structure that reflects the adaptability of the system to the environment, both its decrease and its increase involve less complexity and less flexibility and adaptability to perturbations. Analyses carried out with nonlinear tools have highlighted a link between the alterations of the complexity and the unhealthy states of gait. The functional evaluation of the knee with nonlinear analysis tools is anchored to the theory of optimal variability (Stergiou et al., 2011), at this state the biological system is in a healthy state characterized by the greatest possible effective complexity and reaches high values only in the intermediate region between maximum predictability (excessive order) and no predictability (excessive disturbance). Specifically, the reduction of optimal variability in subjects with ACL deficient knees leads to more rigid and repeatable movement patterns or a state of low complexity and high predictability. On the other hand, in subjects with reconstructed cruciate ligament, the increase beyond the optimal variability is frequent, which generates noisy and irregular movement patterns or a state of low complexity and low predictability (Decker et al., 2011). The vulnerability to pathological changes that occur following ligament injuries can be explained by the association between the loss of variability and the high complexity that leads to the inability to respond appropriately to the changes of the environment. The subtle fluctuations that appear in the kinematic models of the knee undergoing ACL reconstruction are the result of nonlinear interactions that have a deterministic origin and that transmit important information on the behaviour of the system and in particular, provide insight into neuromuscular function after rupture and reconstruction of the ACL.

To study the fluctuations, present during the walk, and specifically, during the walk of subjects with reconstructed ACL, two indicators of nonlinear dynamics are of fundamental importance: the maximal Lyapunov exponent (LyE) and entropy (En).

***Maximal Lyapunov Exponent***

The LyE is an indicator of the stability of a stationary point or a periodic orbit. In the theory of complex dynamical systems, a LyE of a dynamical system provides a measure of how significantly the behaviour of the system is dependent on the initial data, characterizing the presence of chaotic dynamics.

***Entropy***

En is the measure of the chaos of a system. When a system passes from an ordered to a disordered state its entropy increases. There are different techniques for measuring entropy. Approximate entropy (ApEn) is a technique, used in statistics, to quantify the amount of regularity and unpredictability of fluctuations over time series of data. ApEn refers to a "*statistic of regularity*", or the probability that similar observation models are not followed by further similar observations. The value of the ApEn varies between 0 and 2, when ApEn$\cong$0, the analysed time series has greater periodicity and regularity, when ApEn$\cong$2, the time series presents a high unpredictability and irregularity. Sampling entropy (SE) is an alternative method for estimating entropy in real-world data. Unlike the ApEn, the SE calculates the negative logarithm of a probability associated with the time series. Permutation entropy (EP) directly explains the time information contained in the time series. Using the EP evaluates the presence/absence of some patterns present in a time series and it is, therefore, possible to obtain information on the dynamics of the underlying system.

The purpose of this short review is to provide an overview of the nonlinear analysis tools and techniques used in the last twenty years for the functional evaluation of the knee following reconstruction of the ACL by investigating the alterations in the variability between the steps after rupture and reconstruction of the ACL.

## METHODS

In this review, all the scientific articles from 2000 to 2020 were examined using "*ACL*", "*knee*", "*nonlinear*", "*variability*" as keywords for the search. The archives consulted and the search engines used were PubMed, Scopus, Science Direct and Google Scholar. Only studies involving ACL reconstruction and the use of non-linear analysis tools were included in the review.

 

## RESULTS

Table 1. Summary of main results.

| Authors | Year | Purpose | Sample | Instrumentations | Variables | Nonlinear indexes | Conclusions |
|---|---|---|---|---|---|---|---|
| Stergiou et al. | 2004 | Evaluate the effect of walking speed on functional dynamic knee stability. | 10 subjects with ACL rupture. | Optoelectronic system | Joint Angle | LyE | The knee with anterior cruciate ligament deficiency (ACLD) has a more unstable behaviour at the local level than the contralateral regardless of the walking speed, this reduces the ability of the knee to adapt to various perturbations and is an indication of probable future pathologies. |
| Georgoulis et al. | 2006 | Examine how variability during walking is affected by ACL deficiency. | 10 subjects with ACL rupture. | Optoelectronic system | Joint Angle | ApEn | The knee with ACLD moves with more regular and less variable patterns than the contralateral, this generates a loss of complexity: the knee is less able to adapt to the environment and this leads to a probability of any future pathologies. |
| Moraiti et al. | 2007 | Investigate if alterations exist in stride-to-stride variability after ACL rupture in the ACL deficient knee when compared to a healthy control knee. | 7 subjects with ACL rupture.<br>7 healthy subjects with no history of neuromusculoskeletal injury. | Optoelectronic system | Joint Angle | LyE | The knee with ACLD is less variable and less sensitive to initial conditions than a healthy knee, this leads to a loss of system complexity and to possible future pathologies. |
| Moraiti et al. | 2009 | Investigate the functional outcome after anterior cruciate ligament (ACL) reconstruction using bone–patellar tendon–bone (BPTB) and quadrupled semitendinosus and gracilis tendon (ST/G) autografts by evaluating stride-to-stride variability. | 6 male subject who underwent ACL reconstruction with a BPTB autograft.<br>6 male subject who underwent ACL reconstruction with a ST/G autograft.<br>6 healthy subjects who had never suffered any kind of orthopaedic or neurologic condition. | Optoelectronic system | Joint Angle | LyE, ApEn | Both the reconstruction with BPTB and that with ST / G lead to significantly higher ApEn values compared to the healthy control group, this implies a loss of optimal kinematic variability and therefore a decrease in complexity. |

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|---|---|---|---|---|---|---|---|
| Moraiti et al. | 2010 | Examined structure of gait variability after ACL reconstruction with either BPTB or quadrupled ST/G tendon autografts. | 6 male subject who underwent ACL reconstruction with a BPTB autograft.<br>6 male subject who underwent ACL reconstruction with a ST/G autograft.<br>6 healthy subjects who had never suffered any kind of orthopaedic or neurologic condition. | Optoelectronic system | Joint Angle | LyE | The ACL deficient knee has a rigid neuromuscular behaviour and shows greater divergence in the trajectory of movement. |
| Zamplei et al. | 2010 | Investigate the stride-to-stride variability during BW (backward walking) in ACL deficient patients in comparison with a matched control group. | 15 subjects with ACL rupture.<br>11 subjects with no history of neuromusculoskeletal.<br>injury. | Optoelectronic system | Joint Angle | LyE | Both knees of ACLD patients show more rigid walking patterns than healthy controls. The healthy knee of ACLD patients exhibits even more rigid motion patterns than the knee with ACLR. ACL deficiency leads to a loss of optimal variability and therefore to a reduced ability to respond to perturbations. |
| Skurvydas et al. | 2011 | Evaluate possible differences in knee extension and flexion torque variability in the anterior cruciate ligament—deficient (ACLD) leg and their dependence on muscle length and visual feedback (VF). | 13 right leg dominant subject (men) with the right leg ACL deficient one. | Isokinetic dynamometer | Joint Torque | PE | The effect of ACL deficiency on variability (CV) in submaximal isometric knee extension and flexion torque was not significant but flexion torque significantly depended on knee joint angle; PE of knee extension torque was significantly greater in the healthy leg than in the ACLD leg; variability in isometric knee flexion torque (CV) was greater at the short muscle length whereas variability in knee extension torque did not depend on muscle length; and the effect of VF on isometric knee extension and flexion torque variability was significant. |
| De Olivera et al. | 2019 | Assess gait variability after anterior cruciate ligament | 10 subjects observational group I (OG-I, 90 days after ACLR) | Optoelectronic system | Joint Angle | Lye, SEp | The greatest biomechanical stability in the post-operative |

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| | | reconstruction (ACLR), as an indicative of possible altered gait pattern and a measure of recovery compared to control subjects. | 10 subjects observational group II (OG-II, 180 days after ACL reconstruction).<br>10 subjects observational group III (OG-III, 360 days after ACL reconstruction).<br>10 subjects control group, with no ACL reconstruction. | | | | period is recorded 90 days after the ACLR; in the period 180-360 days after the ACLR there is an increase in the recovery of local stability, a slight decrease in local variability and an increase in Sen, this leads to a decrease in the complexity of movement and the cause can be traced to the altered activity muscle that becomes unsaturated following the rupture of the ACL. |
| Lanier et al. | 2020 | Determine how ACL injury, ACL reconstruction (ACLR), and participation in high-performance athletics affect control strategies produced during a novel task that simulates forces generated during cutting movements. | 10 subjects with ACL deficient<br>11subjects after ACL reconstruction<br>10 subjects who were active in more than 50 hrs/year of level I and II sports and no history of ACL injury<br>17 athletes from men's and women's soccer teams were recruited to serve as high-performance athletes | Force Platform | GRF (ground reaction force) | LyE | In the ACLR group, the involved limb exhibited significantly greater LyE values when compared with the uninvolved limb in the AP but not the ML direction. Significantly larger LyE values by almost twofold after ACL injury and reconstruction may identify an aspect of recovery in terms of force control that is not addressed by current rehabilitation protocols that could contribute to the high rates of reinjury in both ipsilateral and contralateral limbs. |

## DISCUSSION

Instrumental analysis of human movement, investigating how a movement is performed, allows to define an ideal execution model and offers the opportunity to compare the model and movement execution. In the studies analysed in this review, the tools used for the instrumental analysis of movement are the infrared optoelectronic system, the force platform and the isokinetic dynamometer. All the studies reviewed in this discussion conducted research on a treadmill and most of them preferred to use a subject-selected self-pacing to minimize the possibility that walking speed was the cause of changes in walking variability. The results obtained by evaluating the LyE and the ApEn show that the knee with reconstructed ACL shows differences in the variability between the steps compared to a healthy knee. In particular, the operated knee has smaller LyE values and is, therefore, less variable and less sensitive to initial conditions than the healthy joint, this can be explained by the altered muscle activity that appears following the rupture of the ACL to compensate for the loss of the ligament. Smaller values of LyE also suggest a loss of complexity, so it can be said that ACL deficiency determines a trend towards greater periodicity and rigidity. The common goal of all the above studies is to examine how ACL deficiency affects the kinematic variability during walking. Various hypotheses have been tested including the direction of walking, speed and the type of graft used for the reconstruction of the ligament, but all the results achieved can be summarized in the loss of complexity, the knee with ACL deficiency moves with patterns of more rigid and less variable movement than the contralateral (and that of a healthy control group), this makes it less capable of adapting to the environment and responding to disturbances with an increased risk of future injuries. The anterior cruciate ligament plays an important role in knee stability not only for its mechanical properties but also for the mechanoreceptors present in it. The loss of proprioceptive inputs coming from the mechanoreceptors present in the ACL could be the cause of the changes that occur at the level of the central nervous system and that lead to the development of altered muscle control and postural synergies. A limitation of the studies examined is related to the use of the treadmill, in fact, Dingwell et al. (2001) found that treadmill walking can affect measures of variability compared to surface walking, however, Matsas et al. (2000) demonstrated that the knee joint kinematics of a familiar treadmill walk can be generalized to surface walking. A further limitation could be the comparison with the contralateral limb and not with the healthy control group, in fact, it has been shown that neuromuscular alterations also appear in the contralateral knee following the rupture and surgical reconstruction of the ACL (Berchuck et al., 1990; Ferber et al., 2004; Moraiti et al., 2007; Stergiou et al. , 2004).

## CONCLUSIONS

The purpose of the surgical reconstruction of the ACL is to restore the function of the knee and prevent the appearance of future pathologies. Using nonlinear tools can be a huge advantage, analysing and understanding the dynamics of motor behaviour as a result of the integration between organism and environment, as suggested by the DST, leads to an innovative and more suitable functional assessment of the joint. A healthy gait is characterized by a state of optimal variability that offers maximum complexity, this state allows flexibility, adaptability and the ability to respond to unpredictable stimuli and solicitations. A non-optimal variability, on the other hand, is highlighted by the inability to respond to environmental changes, which is the cause of further injuries or future pathologies. The analysis of the kinematic variability of the knee provides important information on the changes in neuromuscular function that occur after the rupture and reconstruction of the ACL. Evaluating the functional state of this joint with nonlinear analysis tools, such as the LyE and En, would certainly lead to the improvement of the joint's ability to provide correct proprioceptive information after ACL reconstruction.

 

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